Experimental setup

2.1 Paul traps

From Earnshaw’s theorem\(^1\) [77] it follows, that one cannot trap a charged particle using dc electric fields only. This problem can be circumvented using additional magnetic fields or an ac electric field in at least one direction. In the 1950s, Wolfgang Paul developed the quadrupole ion trap [78], today also called ‘Paul trap’ or ‘rf trap’, which operates through a quadrupole ac electric field that establishes a ponderomotive trapping force for positively charged particles. Such particles, like ions, can be stored in a Paul trap for an, in principle, infinite amount of time. In practice, the trapping duration is dependent on the reaction rate of an ion with molecules from the background gas. In 1989, Paul received the Nobel Prize in Physics ‘for the development of the ion trap technique’. Nowadays, many kinds of Paul traps have been developed, like hyperbolic traps, linear traps, planar traps, or 22 pole traps. Besides high precision spectroscopy, typical purposes for which Paul traps are used are high resolution mass spectroscopy [79], studies of ion-neutral reactions [80,81], quantum computing [82–85], or establishing ion clocks [4]. Experiments at CERN use ion traps to study anti-matter, for example in the GBAR experiment (Gravitational Behaviour of Anti hydrogen at Rest) where an ultracold antihydrogen ion, \(\bar{p}e^+e^+\), is trapped in a Paul trap and, after laser detachment of one positron, the free fall acceleration of created the antihydrogen atom will be measured [86]. This will test Einstein’s weak equivalence principle.

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\(^1\)Samuel Earnshaw developed this idea in 1839 and entitled his publication *On the nature of the Molecular Forces which regulate the Constitution of the Luminiferous Ether*. He calculated the behaviour of Ether particles subjected to electric forces. This was before the concepts of electrodynamics were established and long before constituents of matter like ‘atoms’, ‘ions’ and ‘electrons’ were discovered.
2. Experimental setup

Figure 2.1: Axial view of a linear ion trap (endcaps are not shown here). The diagonally opposing electrode pairs are connected to rf and dc voltages, respectively.

(which states that the trajectory of particles only submitted to gravitational forces is independent on composition or internal structure), directly with matter and antimatter.

In this thesis we describe an experiment in which a linear Paul trap is used which consists of four cylindrical rods. Two diagonally opposing rods are connected to an rf voltage source and the other pair is connected to a dc voltage source, providing confinement of ions in radial direction (See Fig. 2.1). For axial confinement (z-direction) two pairs of dc electrodes, called endcaps, create a nearly harmonic potential at the center of the trap.

2.2 Ion motion in a Paul trap

In this section, we derive the motion of a single trapped ion, following Berkeland’s treatment [87]. In general the electric potential in the radial direction of a linear Paul trap near the trap axis can be written as

$$V(x, y, t) = \frac{V_0}{2} \left( 1 + \frac{x^2 - y^2}{R'^2} \right) \cos(\Omega t) \quad (2.1)$$

where $V_0$ and $\Omega$ are amplitude and angular frequency of the rf and $R'$ is the distance from the trap axis to the electrodes (see Fig. 2.1) and $R' \approx R$. In the limit where the trap electrodes are hyperbolic surfaces of infinite length, $R = R'$. To approximate this condition with cylindrical rods with radius $R_0$ (instead of hyperbolic surfaces) as well as possible, the ratio $R_0/R$ should be chosen close to $1.146$ [88]. The axial confinement is provided by the endcap
2.2. Ion motion in a Paul trap

electrodes, of which the voltages $U_0$ create a dc potential near the center of the trap which can be approximated by:

$$U(x, y, z) = \frac{\kappa U_0}{Z_0^2} [z^2 - \frac{1}{2}(x^2 + y^2)],$$

(2.2)

where $\kappa$ is a geometrical factor and $Z_0$ is half the axial distance between the endcaps. From Eqs. (2.1) and (2.2) we obtain the electric field

$$E(x, y, z, t) = -V_0 \left( \frac{x\hat{x} - y\hat{y}}{R^2} \right) \cos(\Omega t)$$

$$- \frac{\kappa U_0}{Z_0^2} [2z\hat{z} - x\hat{x} - y\hat{y}].$$

(2.3)

Newton’s second law, in the form of $E_i Q = m\ddot{u}_i$, gives us the equations of motion for a single trapped ion with charge $Q$ and mass $m$:

$$\ddot{u}_i + [a_i + 2q_i \cos(\Omega t)] \frac{\Omega^2}{4} u_i = 0,$$

(2.4)

where $u = u_x \hat{x} + u_y \hat{y} + u_z \hat{z}$ is the position of the ion with respect to the minimum of the trap potential, and

$$a_x = a_y = -\frac{1}{2} a_z = -\frac{4Q\kappa U_0}{mZ_0^2 \Omega^2},$$

(2.5)

and

$$q_x = -q_y = \frac{2QV_0}{mR^2 \Omega^2}, \quad q_z = 0.$$

(2.6)

Equation (2.4) is called the Mathieu equation, named after Émile Léonard Mathieu. If we take $q_i \ll 1$ and $a_i \ll 1$, which is typically the case, the first-order solution of the Mathieu equation is

$$u_i(t) \approx u_{1i} \cos(\omega_i t + \phi_{Si})[1 + \frac{q_i}{2} \cos(\Omega t)],$$

(2.7)

where $\omega_i \simeq \frac{\Omega}{2} \sqrt{a_i + \frac{1}{2} q_i^2}$ and $\phi_{Si}$ is a constant phase offset which is determined by the initial position and velocity conditions. The term $\omega_i$ represents the secular motion of a trapped ion while the $\cos(\Omega t)$ term corresponds to the micromotion.

The values for $a_i$ and $q_i$ which provide stable and unstable solutions for ions can be expressed in a stability diagram. Figure 2.2 shows the values of these parameters in two dimensions for the case of an infinitely long linear Paul trap.

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2 Mathieu introduced this equation in 1868 in order to calculate the motion of vibrating elliptical drumheads. Ion traps were unknown at that time.
2. Experimental setup

Figure 2.2: Stability diagram of an infinitely long linear Paul trap in two dimensions. Stability regions occur also for larger values of $a$ and $q$, but only the lowest stability region is shown here. The dashed and solid lines correspond to the boundaries of stable solutions of the Mathieu equation in the $y$ and $x$-directions, respectively.

To lowest order, the pseudopotential is given by $\frac{1}{2}m\omega^2q^2$. Obviously trapped particles will be lost if they hit the electrodes, so an upper limit to the trap depth is approximately given by $\frac{1}{2}\omega^2R^2$. Note that the trap depth depends on the charge-to-mass ratio of the trapped particles, which is used to selectively remove heavy impurity ions from the trap (see Sec. 4.3).

In ion traps one often deals with multiple ions trapped at the same time. For sufficiently cold ensembles, such that crystallization occurs, the amplitudes of the secular motion of each ion in the crystal can be obtained from solving the eigenfrequencies and eigenmodes of the system (see for example [89]). Such a treatment is valid for ion crystals with temperatures of order 1 mK. For warmer ion ensembles (temperature $\gg$ 1 mK), in which individual ions may have sufficient energy to hop from lattice site to lattice site and the crystal becomes partly melted, molecular dynamics (MD) simulations provide a more realistic prediction of the ion motion (Appendix A).

2.3 Linear Paul trap in this experiment

We use a linear Paul trap that consists of four cylindrical molybdenum rods with a length of 60 mm and a diameter of 8.0 mm, of which two diagonally opposing rods are connected to a 13.2 MHz rf voltage source. With $R = 3.5$ mm, the ratio $R_0/R = 1.14$, which is close to the optimum value of 1.146 (Sec. 2.2). The rf amplitude at the location of the ions is about 270 V. The other pair of opposing rods is segmented into five parts of 12 mm length. Each of the segments is ac-coupled to ground (Fig. 2.6), so that, controlled dc voltages can be applied which can be adjusted individually while keeping each electrode at rf ground at all times. This arrangement allows compensating stray electric
2.3. Linear Paul trap in this experiment

Figure 2.3: Schematic three-dimensional representation of the ion trap electrodes. The two rf electrodes are connected to an rf voltage source oscillating at 13.2 MHz frequency. The other labeled electrodes are ac-coupled to rf ground, and connected to dc voltage sources. With electrode pairs 2,7 and 4,9 configured as endcaps the ions are trapped in between electrodes 3 and 8.

fields due to excess charge that may have accumulated at parts nearby the ions. Only the first three pairs of segments are operational during ion trapping. A schematic drawing of the trap is shown in Fig. 2.3, and a picture of the trap (taken during maintenance of the trap) is shown in Fig. 2.4.

Electrode numbers 2, 7, 4 and 9 serve as endcap electrodes which are connected with a dc voltage of 4 V, and provide confinement in the axial direction. Near the center of the trap the potential is approximately harmonic. Note that since the 4 V endcap voltage is applied to only two of the four rods, the endcap potential at the trap axis is only \( \sim 2 \) V. A finite-element analysis performed in SIMION 6.0 yields (with \( Z_0 = 6 \) mm) a geometric factor \( \kappa = 0.144 \), so that for an endcap voltage of 4 V the axial frequencies of \( \text{Be}^+ \) and \( \text{HD}^+ \) become 93 kHz and 161 kHz, respectively. The center electrode pair (numbers 3 and 8) is connected to \( \sim 0 \) V with respect to ground. Electrode number 3 is connected to an rf source producing frequencies in the range of 0.1-2 MHz which are used to excite the secular motion of the trapped ion species. In this trap, secular excitation frequencies of \( \text{Be}^+ \) and \( \text{HD}^+ \) ions are obtained at \( \sim 290 \) kHz and \( \sim 830 \) kHz respectively.

Phase differences between the two rf channels in the order of one degree can lead to ion micromotion heating which leads to temperatures of hundreds of mK [87]. To minimize this effect, the two rf circuits at the electrical feed through of the vacuum chamber leading to the rods are electrically connected by 3 \( \mu \)F ceramic capacitors (with electrical leads of only a few mm length to avoid significant stray inductance); see Fig 2.5. An electrical circuit simulation performed with SPICE software shows that this measure reduces the potential phase difference to \(<4\) millidegrees.
2. Experimental setup

Figure 2.4: Picture of the ion trap used in this experiment, and the OFHC copper structure onto which the trap is mounted. The picture was taken after installation of three new e-guns (thoriated tungsten wires) which are mounted above the trap electrodes.

2.3.1 Helical resonator

The sinusoidal rf voltage is derived from an arbitrary waveform generator (AWG), whose amplitude and frequency can be controlled externally through a GPIB interface. The AWG output is sent through an rf amplifier, resulting in an rf amplitude of 15-20 V. To achieve the ∼300 V needed to trap ions, the amplifier output is connected to a helical resonator, which acts as a step-up transformer (Fig. 2.5). The secondary coil of the helical resonator (which connects to the rf electrodes) is of the bifilar type, i.e. it consists of an identical pair of galvanically isolated wires. This allows applying different dc voltages to each of the rf electrodes. The helical resonator is placed outside the vacuum, on top of the vacuum housing. With the trap connected, the helical resonator has a Q factor of 43 and its resonance frequency is approximately 13.2 MHz. Figure 2.5 shows a schematic design of the helical resonator. The coils are shielded by an oxygen free high conductivity (OFHC) copper housing. The top of the resonator is covered by a brass disk which is tightly clamped to the shield. The disk contains a BNC feed through onto which the rf coupling antenna is mounted. Two teflon-coated wires are pressed against the two pins.
2.3. Linear Paul trap in this experiment

Figure 2.5: A schematic view of the helical resonator. A bifilar secondary coil (grey, with the two wires indicated by solid and dashed lines, respectively) is inductively coupled to the primary coil (black), which is connected to the rf voltage source. The dc voltages on each wire of the secondary coil can be adjusted individually.

... of the vacuum feedthrough, and are guided to BNC connectors via the stainless steel vacuum flange using metallic tape. These identical wires act as rf pick-up antennae and are used to estimate the phase and amplitude at the rf electrodes in the trap. The pick-up antennae were calibrated for a wide range of rf voltages before the installation of the helical resonator.

2.3.2 Stabilization of dc voltages on electrodes

To realize an rf ground at the dc electrodes, each dc electrode is connected to an RC filter with the resistor placed in the dc path (Fig. 2.6a). The values of the components are selected such that a corner frequency of 1.6 kHz is achieved, well below the 13.2 MHz rf frequency. Moreover, only voltages with Fourier components below this value are efficiently transmitted from the dc voltage...
2. Experimental setup

Source to the trap electrodes, thus suppressing possible voltage noise at secular trap frequencies which are typically in the range 50-900 kHz.

With a capacitor value of 1 nF, a resistor value of 100 kΩ is required yields the 1.6 kHz corner frequency. However, during loading of ions by electron bombardment (Sec. 2.5), the emission current of the electron gun is dissipated mostly by the trap electrodes, leading to currents up to 10 µA. In combination with the 100 kΩ resistor, this may increase the voltage at the electrode by as much as 1 V, which is of the same order as the trap depth.

To ameliorate this effect, the trap electrodes are connected to an electrical circuit which actively stabilizes the voltage at each electrode irrespective of the current dissipated by it. This circuit is shown in Fig. 2.6 and was first described in [90].

2.4 Vacuum housing and trap mount

Figure 2.7 shows a schematic view of the stainless steel vacuum housing. The trap is mounted on an OFHC copper tube, which is mounted vertically from the top flange of the vacuum chamber. This tube consists of a tube and a (bifilar) center conductor, similar to a coaxial waveguide. The rf outputs of the helical resonator (located on the outside of the vacuum chamber) are connected to two OHFC pins of a vacuum feedthrough, which feed into the two segments of the bifilar center conductor. These segments are galvanically isolated by Kapton sheet, and connected by screws made of alumina (amorphous Al₂O₃) ceramic. At the end of the center conductor, the two segments are connected by two additional 1 nF chip capacitors (Novacap) placed in parallel to minimize any rf voltage and phase differences between the segments. From there, two molybdenum wires of equal length feed the rf and dc voltages of each segment to an rf conductor.

The reentrant view ports on the vacuum housing are ConFlat (CF) flanges of 150 mm outer diameter (Larson Electronic Glass, SQ-300-F6), which are sealed with 313 nm anti-reflection coated fused silica viewports with a diameter of 65 mm. Apart from apertures providing optical access parallel and perpendicular to the trap axis, the vacuum chamber is equipped with several CF 40 flanges giving optical access at an angle of 17 degrees with respect to the trap axis. One of these flanges is connected to a leak valve mechanism that is connected to an HD lecture bottle. The leak valve can be opened with a stepper motor which allows introducing small and reproducible amounts of HD gas into the vacuum. The HD gas can be ionized to HD⁺ within the vacuum system (see Sec. 2.5). Below the vacuum housing, two turbo pumps and a backing pump are connected series. In addition, the vacuum chamber is fitted with a titanium sublimation pump. After a one-week bakeout of the
2.4. Vacuum housing and trap mount

Figure 2.6: Electrode-voltage stabilization circuitries for the dc (a) and rf (b) electrodes employing an reversed operational amplifier. In case a trap electrode connected to the negative input of the operational amplifier dissipates a current $I_{em}$ (e.g. electrons emitted by the electron gun during loading of ions), the resistors at the output of the op-amp convert the dissipated current to exactly the voltage required at the positive input terminal of the op-amp to maintain the set voltage $V_s$ at the electrode.
2. Experimental setup

Figure 2.7: Computer-assisted-design (CAD) drawing of a cross section of the vacuum housing, including the ion trap and support structure (center), and one of the re-entrant viewports (translucent tube protruding from the back towards the trap). This drawing was made in Inventor.

vacuum chamber at 200 °C, a room-temperature pressure of $\sim 1 \times 10^{-10}$ mbar is obtained, as found from an Bayard-Alpert type ion gauge (Granville-Phillips 274).

2.5 Loading ions

In order to load ions in the trap, HD molecules from an HD gas bottle, and beryllium atoms evaporated from a beryllium oven (see below), are ionized through electron impact ionization. The ionizing electrons are delivered by a negatively biased electron gun (e-gun) which is a thoriated tungsten filament situated near the ion trap (see Fig. 2.4). The basic principle of operation is as follows. The filament is heated by a bias current in order to produce a
significant amount of thermo-electrons. The negative bias voltage subsequently accelerates these electrons away from the filament, and during certain phases of each trap rf cycle some electrons will traverse the center of the trap, where they may collide with neutral Be or HD particles. In total, three e-guns are installed, but during the experiment only one (left one in Fig. 2.4) is used. The maximum electron impact ionization cross sections for Be$^+$ and HD$^+$ are near 50 eV and 120 eV of electron energy, respectively [91]. The energies at which electrons arrive at a Be atom or HD molecule depends on the difference between the e-gun bias voltage and the instantaneous rf potential at the time of impact. Optimal e-gun bias voltages for loading Be$^+$ and HD$^+$ turn out to be $-40$ V and $-200$ V, respectively. In order to load ions, approximately 1 A of filament current is sent through the e-gun, which results in an emission electron current of $\sim 20 \, \mu$A. The emission current is exponentially dependent on the filament temperature, and therefore, in order to load ions in a reproducible manner, the emission current is stabilized with a servo loop system. The circuit diagram of this servo loop is depicted in Fig. 2.8. One salient feature of this setup is that it operates in galvanically separated domains, namely that of the $\pm 15$ V control electronics, and the part which controls the filament current which is biased at $-40$ to $-200$ V. This is achieved by use of an opto-coupler which connects the e-gun part with the servo circuitry, thus preventing a high voltage at the servo system part.

2.5.1 Beryllium oven

The beryllium oven design was originally developed at the National Institute of Standards and Technology by P.O. Schmidt and T. Rosenband. The oven consists of a four-bore Al$_2$O$_3$ tube, of about 5 mm length and 1.2 mm outer diameter. Each bore has an inner diameter of 0.25 mm. A tantalum wire with 0.25 mm diameter is looped through three of the bores, while the remaining bore is filled with a 0.25-mm-diameter beryllium wire of a few millimeter length. To fix the beryllium wire, one end of the ceramic tube is filled with ceramic paste (Aremco Ceramabond 569-VFG), and subsequently cured for two hours at 90 $^\circ$C in an oven.

By sending a current through the tantalum wire, the oven is heated. In order to achieve a sufficiently high beryllium vapor density, the oven should be heated to about 1300 to 1400 K. For an oven at such temperatures mounted in free space, a considerable amount of heat is lost by radiation, and the current through the tantalum filament needed to balance the radiation loss might break the filament. To reduce the burden on the filament, the oven is suspended in a 2.5-mm-wide cylindrical hole inside an aluminum part, such that a part of the radiation is reflected back onto the oven instead of being radiated away, and the current can be reduced to a more tolerable level. Heating the tantalum
Figure 2.8: The emission current stabilization scheme of the electron gun. The emission current is converted to a voltage at the 180 kΩ resistor placed at the input of the µA meter. This voltage serves as input for the servo electronics, which controls the emission current by adjusting the filament current through a MOSFET (IRF 5320). An opto-coupler (SFH 615 – 3) separates the high voltage (−40 V or −200 V, adjustable by a relay switch) from the servo loop circuitry (left side).
wire with \( \sim 3 \) A is sufficient to evaporate a sufficiently large number of beryllium atoms, of which a small part will be ionized and trapped. The oven is covered with an aluminum cone that shields the rest of the vacuum chamber from excessive contamination by a (conductive) layer of beryllium. Evaporated beryllium atoms only escape through the small hole on top of the cone.

2.6 The UV laser-cooling system

In order to reduce the Doppler broadening of the \((v,L):(0,2)\rightarrow(8,3)\) transition linewidth, the HD\(^+\) molecules need to be cooled to the millikelvin range. Since HD\(^+\) cannot be cooled with a laser, Doppler-cooled Be\(^+\) ions are used for sympathetically cooling of the HD\(^+\) molecules. For Doppler cooling of Be\(^+\), a 313 nm laser is used which is essentially a frequency-doubled 626 nm continuous-wave (cw) ring dye (sulforhodamine B) laser. This laser is pumped by 8 W of cw 532 nm light from a Nd:YVO\(_4\) (Spectra-Physics Millennia X) laser. The frequency doubling is carried out by directing the 626 nm laser through a Brewster-cut \( \beta \)-barium borate (BBO) crystal housed in a bow-tie shaped enhancement cavity. The latter is kept resonant with the 626 nm laser frequency using a H"ansch-Couillaud locking scheme \[92\]. About 0.6 W is generated from the dye laser which, after a beam splitter for laser stabilization optics and transmission through an optical fiber, is converted to at most 10 mW of 313 nm. After the doubling cavity, cylindrical and spherical lenses are used to realize a beam waist of the 313 nm beam at the location of the ions of \( \sim 150 \) \( \mu \)m.

Selection rules provide a possibility to Doppler cool Be\(^+\) without the use of any repumping lasers. The level scheme of the cooling transition is shown in Fig. 2.9. By using circularly polarized light directed along the quantization axis, \( \sigma^- \) and \( \sigma^+ \) transitions will ensue between the \( ^2S_{1/2} (F = 2) \) and \( ^2P_{3/2} \) levels in Be\(^+\), which have a corresponding linewidth of \( \Gamma = 2\pi \times 19.4 \) MHz. This is an almost closed cooling transition which is sufficient to cool trapped Be\(^+\) ions down to a few millikelvin. In order to generate circularly polarized light of high purity, the 313 nm beam is directed through a Glan-Taylor polarizer and a zero order quarter wave plate. Furthermore, to achieve a closed cycling transition, it is essential to align the quantization axis with the propagation direction of the light. For this reason, three orthogonal pairs of Helmholtz coils are installed around the vacuum system, generating a small B-field (1.9 G) which can be precisely aligned along the direction of propagation of the cooling laser. The 313 nm fluorescence is detected with a photomultiplier tube (PMT) and an electron-multiplied charge-coupled-device (EMCCD) camera at an angle of 90 degrees with respect to the trap axis (see Fig. 4.3).

The frequency of the 626 nm laser is locked to a fringe of a Fabry-Perot cavity which is locked to a HeNe laser with a maximum frequency drift of
2. **Experimental setup**

**Figure 2.9:** A diagram of relevant lines of the 313 nm laser cooling transition in Be$^+$. The thick arrow represents the $\sigma^{\pm}$ cooling transitions. The dashed arrows represent the dominant spontaneous channels from $F=0,1,2,3$ states. Non-perfect circularly polarized 313 nm light may lead to $\pi$ transitions which lead to a small population of the $^2S_{1/2}(F=1)$ dark state.

**Figure 2.10:** EMCCD camera image of a large Coulomb crystal with a height of approximately 100 $\mu$m. In the center of the Be$^+$ ion crystal a dark core is situated consisting of HD$^+$, H$_2$D$^+$ and HD$^+_2$. This crystal has temperature of $\sim$6 mK.
1 MHz per day. An AOM is placed within the optical path that is part of the servo loop of the Fabry-Perot cavity and the 626 nm laser. As discussed in detail in Chapter 3, this system offers the possibility to tune the 626 nm light over a frequency range of 30 GHz with a speed of 500 MHz/s without losing the frequency lock. Further details about this system are described in [75] and [93].

2.7 Spectroscopy laser setup

In order to probe the \((v,L):(0,2)\rightarrow(8,3)\) transition, a continuous-wave titanium:sapphire laser at 782 nm is used. This laser is pumped by 6 W of a 532 nm Nd:YVO\(_4\) (Spectra-Physics Millennia V) laser. We use a self-referenced frequency comb in order to stabilize the frequency of the 782 nm light. The frequency comb itself is locked to a rubidium atomic clock for short-term stability. For long-term traceability to the SI second, the rubidium clock is disciplined to the pulse-per-second output of a GPS receiver, located on the roof of the building. The 782 nm light is transferred to the frequency comb (which is located in another laboratory) through a polarization-maintaining (pm) optical fiber. There, the 782 nm laser is mixed with the output of the optical frequency comb to produce a beat note at 63.5 MHz, which is amplified and counted by a frequency counter (Agilent 53132A). The beat note signal from the counter is sent back to the 782 nm laser laboratory and used to generate an error signal as input for a digital servo loop. A schematic overview of the setup is shown in Fig. 2.11. More details of this system are given in Chapter 4.

2.8 Computer control system

The software for control of the setup is written in Python and provides a high level of automation. By using the TkInter graphical user interface (GUI) in combination with a touch screen, complex and parallel experimental routines can be started with a single tap at the screen, such as the secular scan-REMPD-secular scan measurement scheme shown in Fig. 4.5. The computer interfaces physically with the experimental setup through a National Instruments (NI) GPIB and PCI6023 card (analog or TTL outputs). For data acquisition (DAQ) the PCI6023 card and two NI USB6009 DAQ devices are used. To communicate at the level of native NI software (NI-DAQmx), the Python software uses a wrapper based on the ctypes library and a C-library of DAQmx commands. A similar approach is followed for the communication between the Python software and the EMCCD camera (Andor iXon DU885-KCS-VP).
2. Experimental setup

Agilent counter frequency comb laser
532 nm Nd:YVO
4 laser
782 nm Ti:S laser
λ meter
digitalservo loop
stabilized 782 nm to ion trap
APD
Amplifier
bandpass filter

Rb atomic
clock
GPS

pm /f_iber
network connection
grating
_lens
splitter cube

Figure 2.11: A schematic view of the Ti:S laser and the setup for frequency locking. The 782 nm Ti:S laser is pumped by 532 nm light and is directed to a wavemeter, the ion trap and to the frequency comb laboratory. The combination of the grating, lens and slit serves as a spectral filter which reduces the intensity on the avalanche photodiode (APD) by transmitting only the comb modes close to 782 nm. The beat note (63.5 MHz) of the overlapping 782 nm and frequency comb beams is detected with an APD and amplified. An electronic bandpass filter cuts off frequencies that differ by more than 5 MHz from the beat-note frequency. The beat note is counted, and the result is sent back to the ion trap laboratory and used by a digital servo loop in order to lock the 782 nm laser cavity.

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